PIP – Linac Modulator Specification Data

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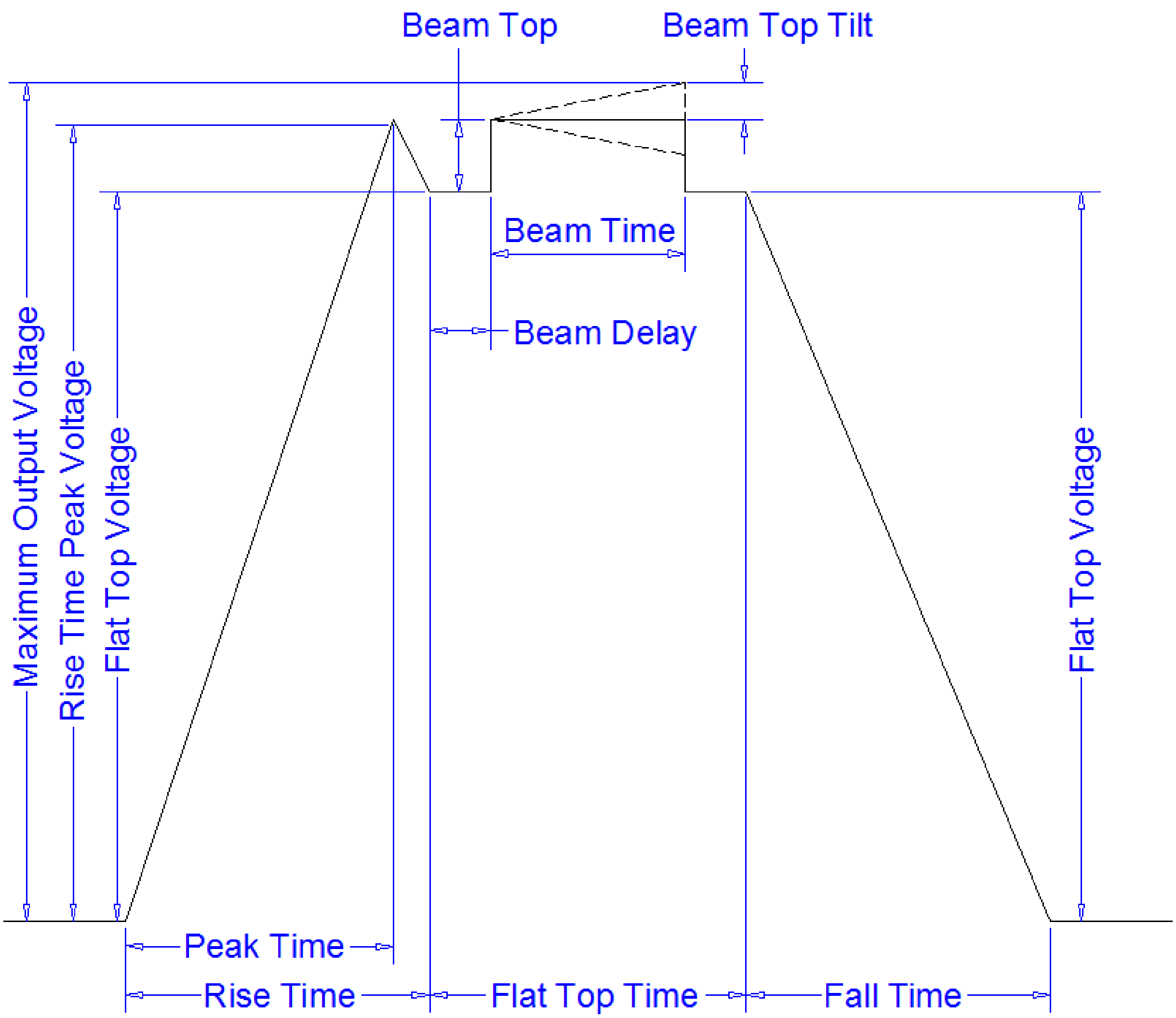
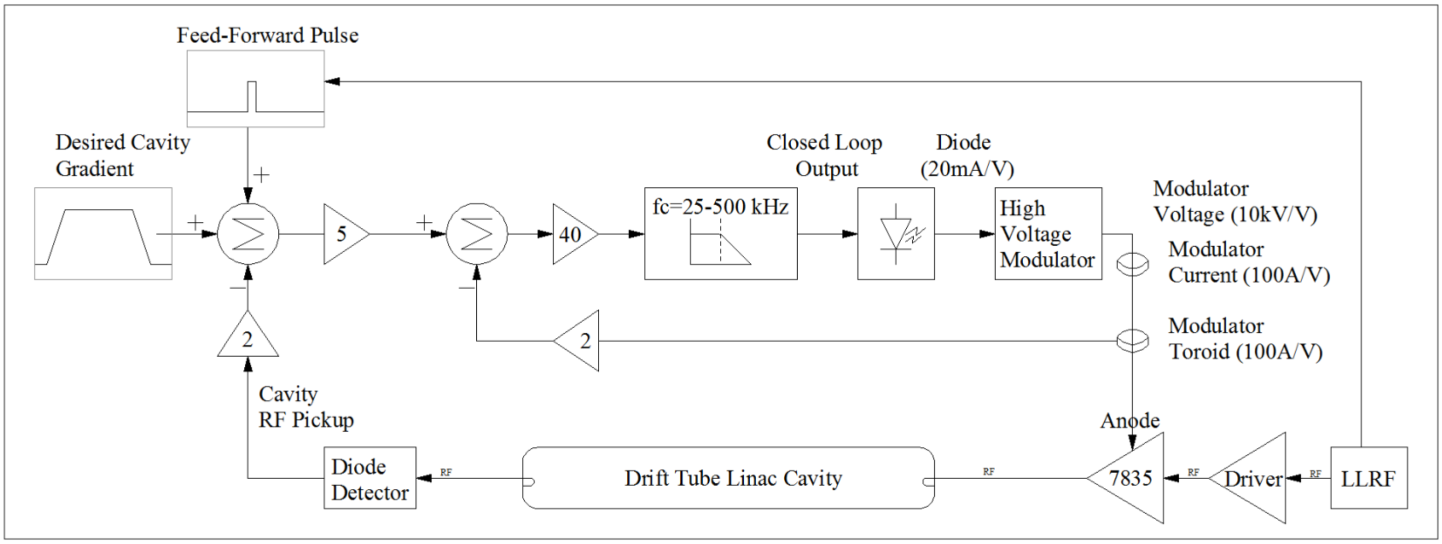
December 13, 2011

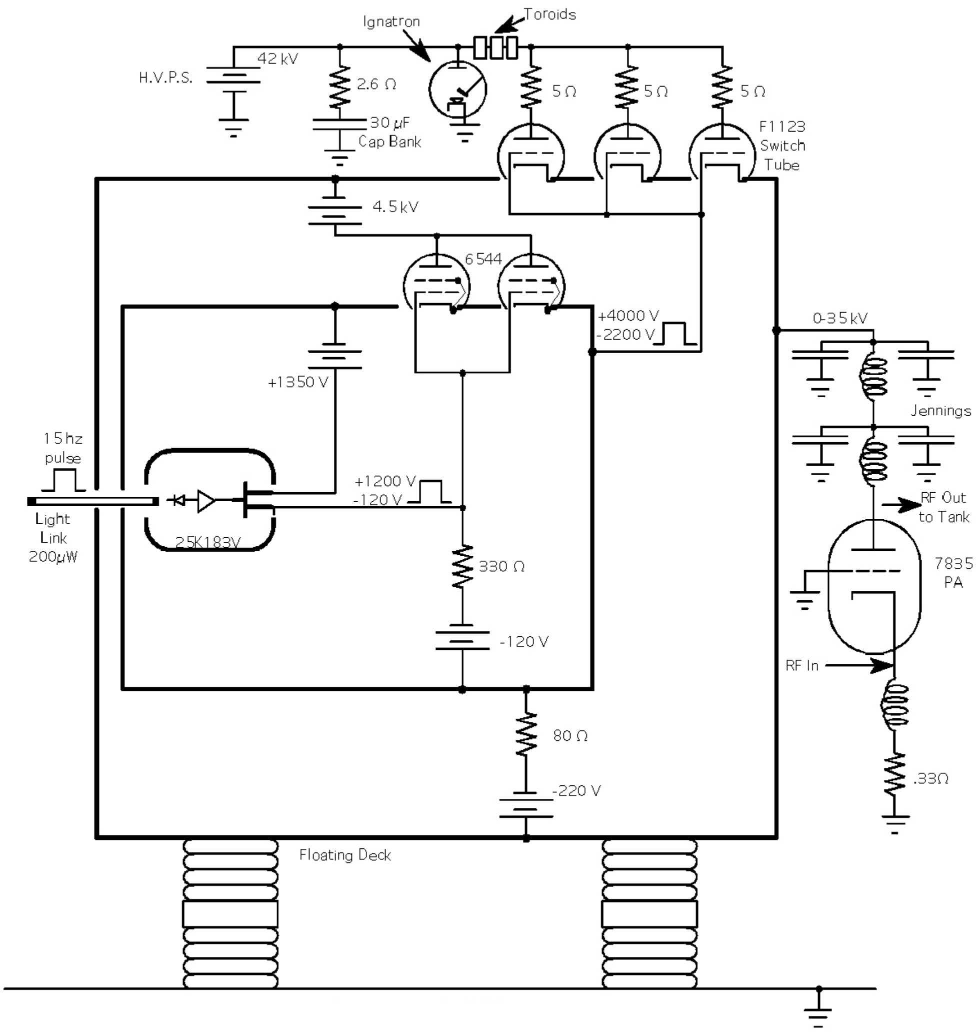
Introduction

This document is not written to be a complete description of the Fermilab Linac 7835 power amplifier (PA) modulator, but instead, is a listing of much of the study data taken on our operating modulators in an effort to properly specify a new modulator design. The plot below is used throughout the paper to describe many of the specifications.



Present System Block Diagrams





Pulse Repetition Rate (15Hz max)

This is mainly a Booster limitation on frequency repetition and an operations standard for 40+ years. It is also a limitation on the cooling and RF system in Linac.

Rise Time & Fall Time (50-150 us rise & 70-150 us fall)

In order determine appropriate rise and fall time specifications for the new modulator, we looked at the effects of rise and fall time on cavity fields. Since the modulator voltage pulse is similar to the output power pulse, minus the effective cavity impendence and saturation effects, we can assume that the rise/fall time of the forward power to the cavity closely matches the modulator voltage waveform. I assumed a peak power of 3 MW on the flat top (aka. steady state) region of the pulse. The present maximum is 2.8 MW on our running RF systems. I took the following data, along with the cavity model created by Ed Cullerton during the LLRF upgrade to study the effects of rise/fall time on reverse power. We know from theory the following equations (RF Linear Accelerators by Thomas Wangler 2008 pages 139-148)

Assuming $I_{beam} = 42\text{ mA}$, then $\beta = 1.756$

$$Q_0 = 65047$$

$$Q_L = \frac{Q_0}{1+\beta} = \frac{65047}{1+1.756} = 23602$$

$$R_{cav} = \frac{R_{shunt}}{1+\beta} = \frac{934.883\times10^6}{1+1.756} = 339.22\times10^6$$

$$L_{cav} = \frac{R_{cav}}{\omega_0 \times Q_0} = \frac{339.22\times10^6}{2\pi\cdot201.25\times10^6\cdot65047} = 4.124\text{ uH}$$

$$C_{cav} = \frac{Q_0}{\omega_0 \times R_{cav}} = \frac{65047}{2\pi\cdot201.25\times10^6\cdot339.22\times10^6} = 0.1516\text{ pF}$$

$$T_{cav} = \sqrt{\frac{R_{cav}}{Z_0\beta}} = \sqrt{\frac{339.22\times10^6}{50\cdot1.756}} = 1965$$

$$\frac{R}{Q} = \frac{2\cdot R_{cav}}{Q_0} = \frac{2\cdot339.22\times10^6}{65047} = 10430$$

$$R_L = \frac{R_{cav}}{T_{cav}^2} = \frac{339.22\times10^6}{1965^2} = 87.784$$

$$L_L = \frac{L_{cav}}{T_{cav}^2} = \frac{4.124\times10^{-6}}{1965^2} = 1.067\text{ pH}$$

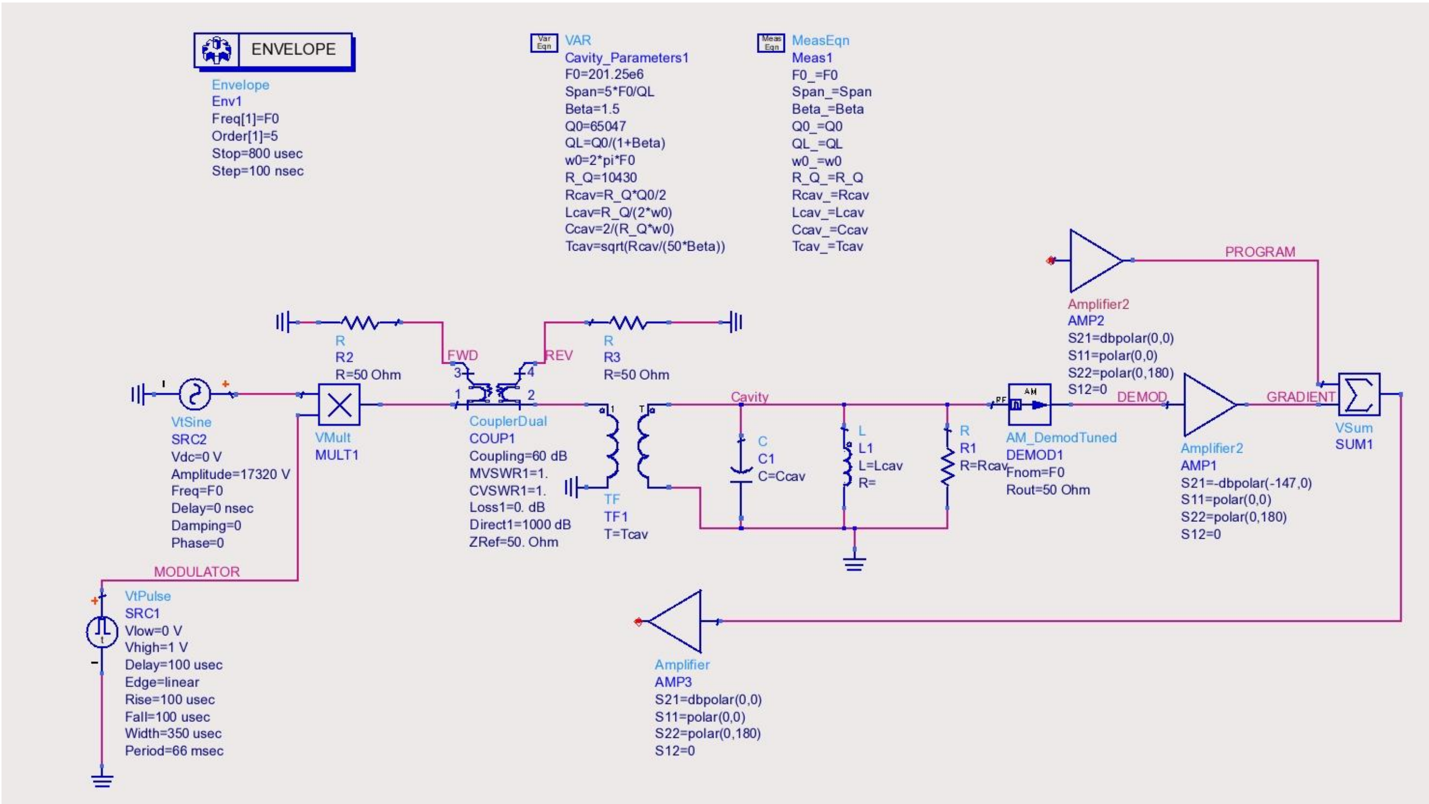
$$C_L = C_{cav}\cdot T_{cav}^2 = 0.1516\cdot1965^2 = 0.5862\text{ uF}$$

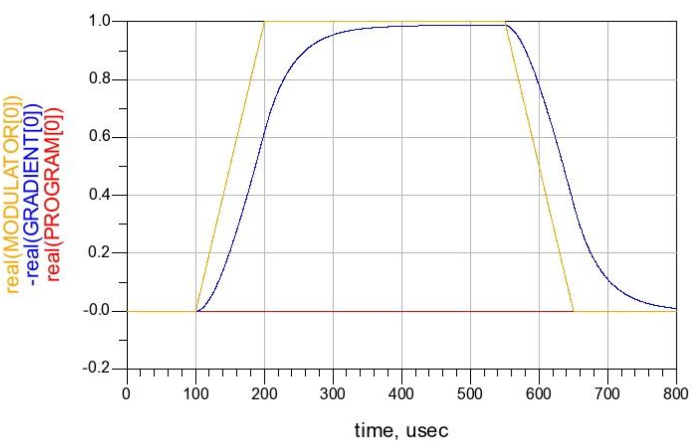
$$P_{\text{Reverse (steady state)}} = P_{\text{Forward}}\left(\frac{\beta-1}{\beta+1}\right)^2 = 0.07525\times P_{\text{Forward}} = 0.07525\times3 = .226\text{ MW}$$

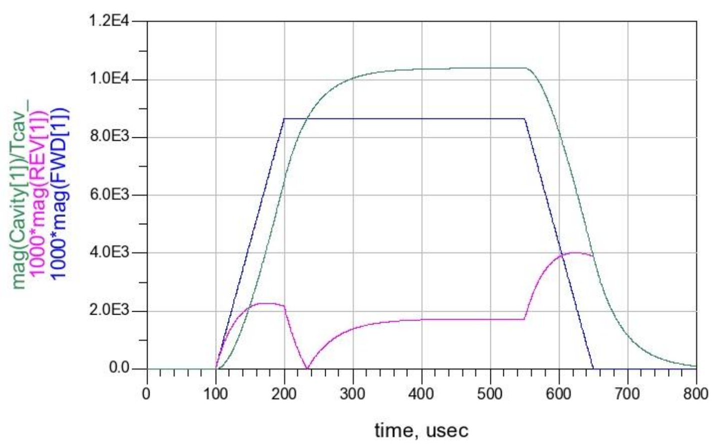
The cavity time constant is a very important parameter since it is the major factor contributing to settling time of the fields in the cavity.

$$\tau_{cavity} = \frac{2Q_L}{\omega_0} = \frac{2\cdot23602}{2\pi\cdot201.25\times10^6} = 37.33\ \mu\text{s}$$

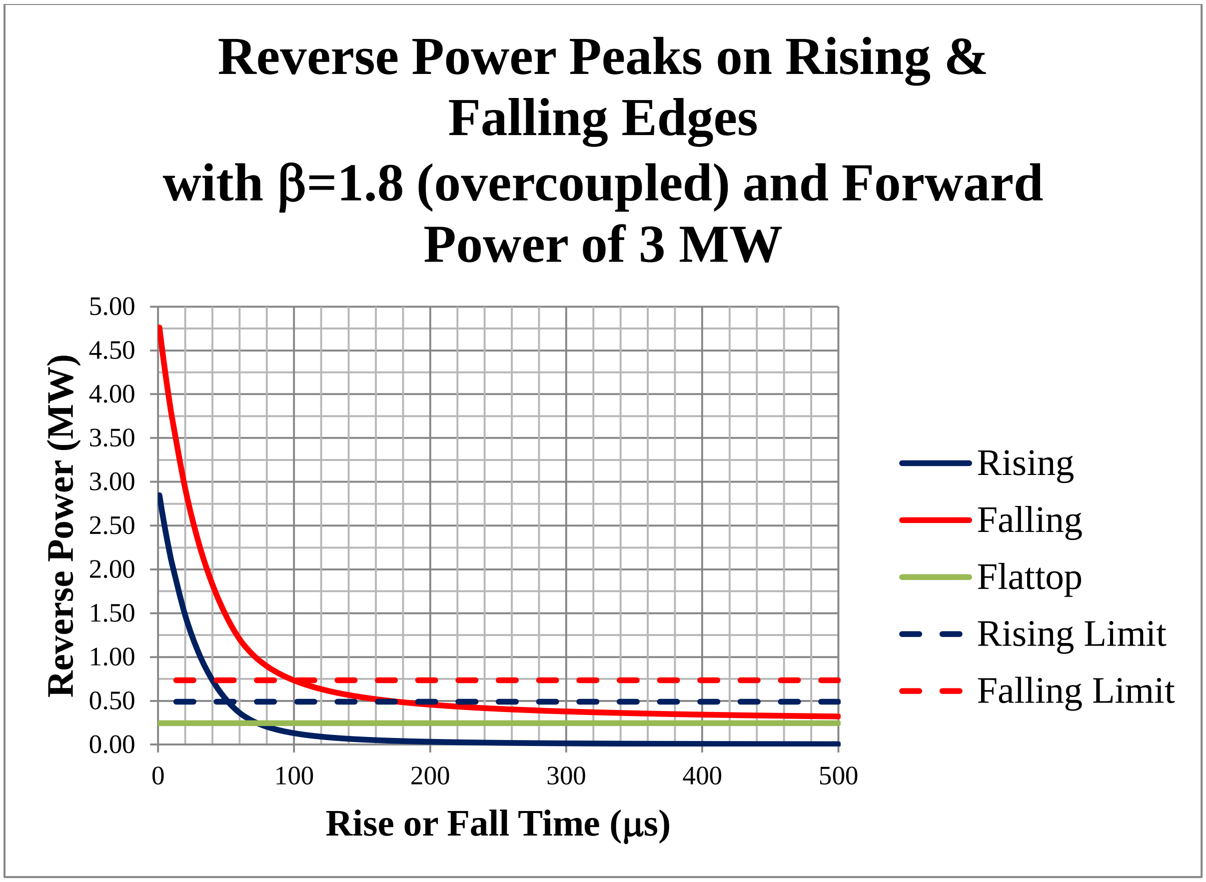
This data was then placed into the following model in Agilent ADS

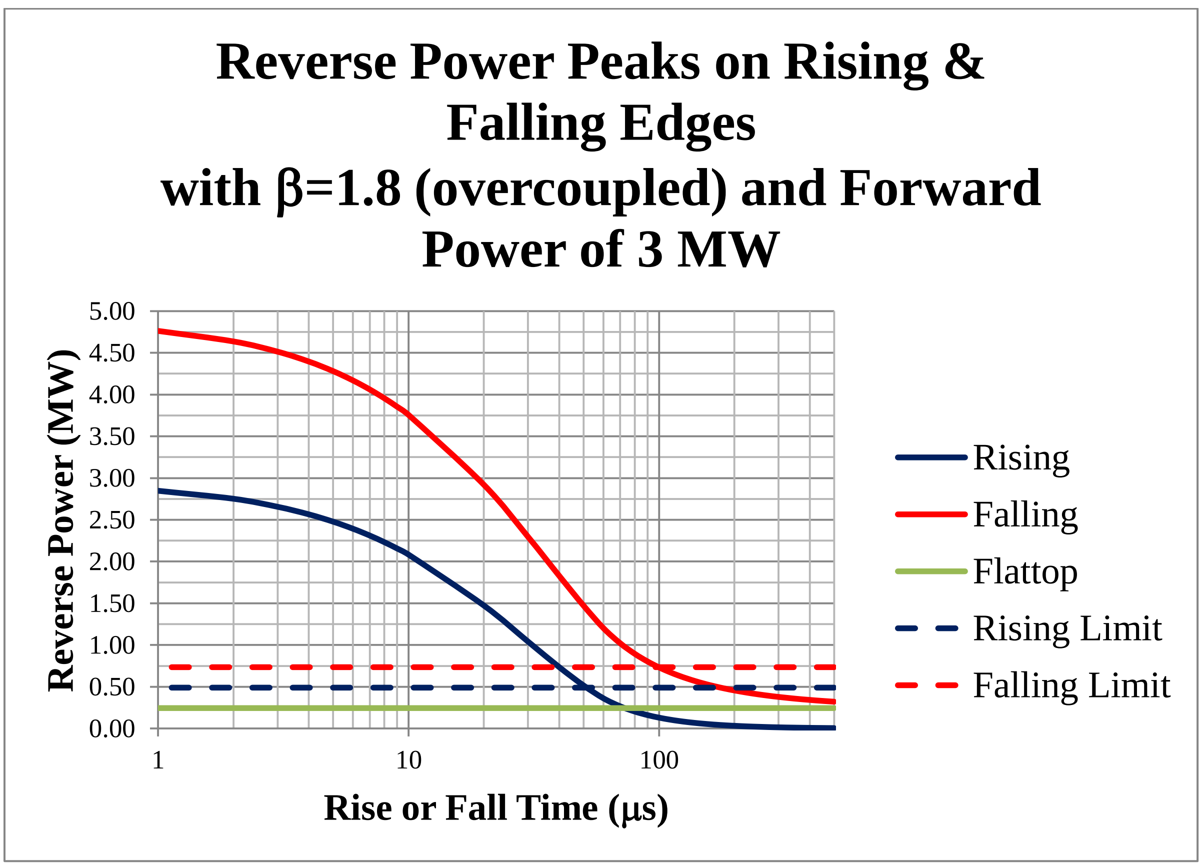






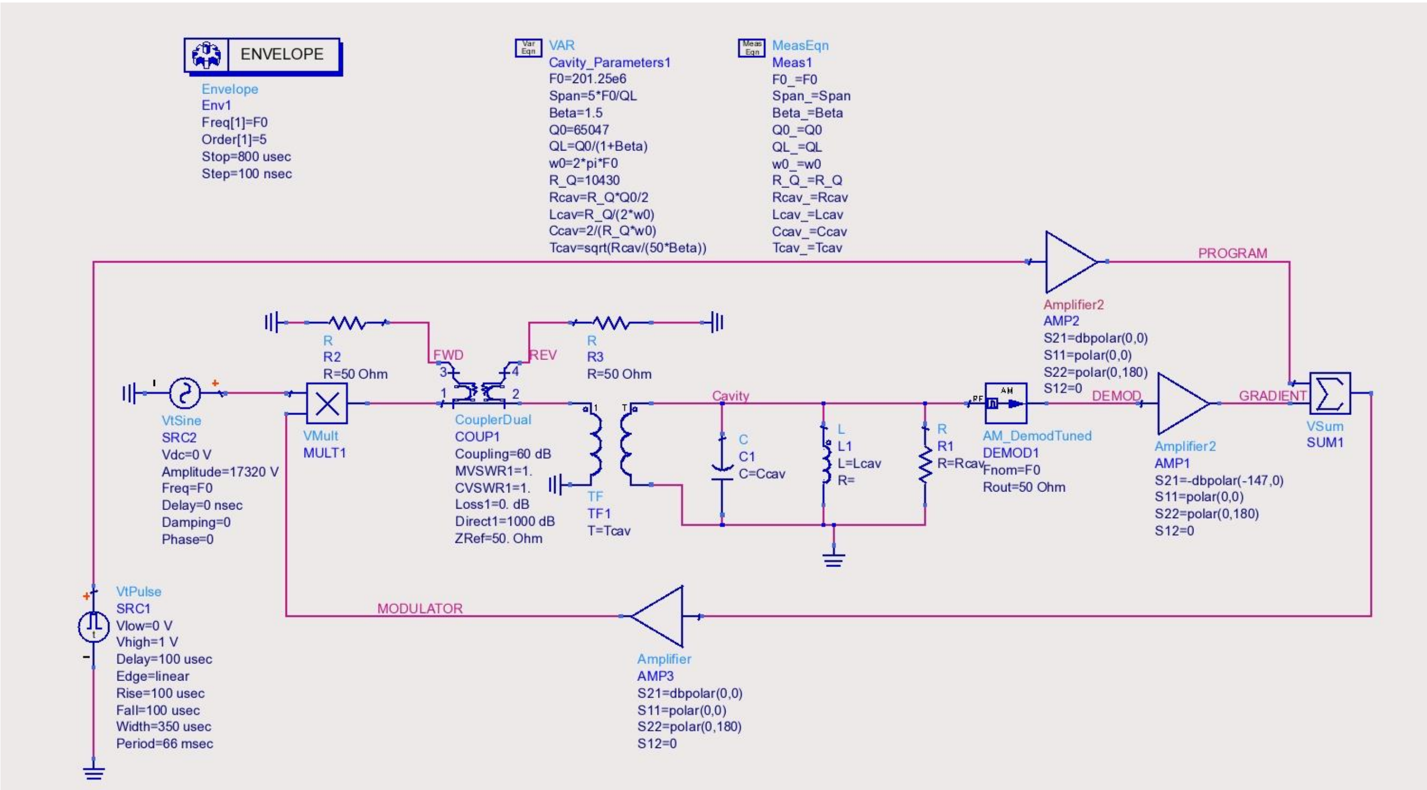
This model was then adjusted to run at different rise and fall times, and the peak power for both the rising and falling edges where calculated and plotted on the next page. The rise and fall times are dependent on the characteristics of the Linac modulator RF feedback loop topology, most notability, the cavity over coupling. The current system runs at 100 us rise and fall times for the cavity fields. The data shows that we could accept a faster rise time of about 50 us, and would run better on a lower fall time of about 150 us. This will be helpful since we need to overshoot the modulator to keep the gradient settling time acceptable

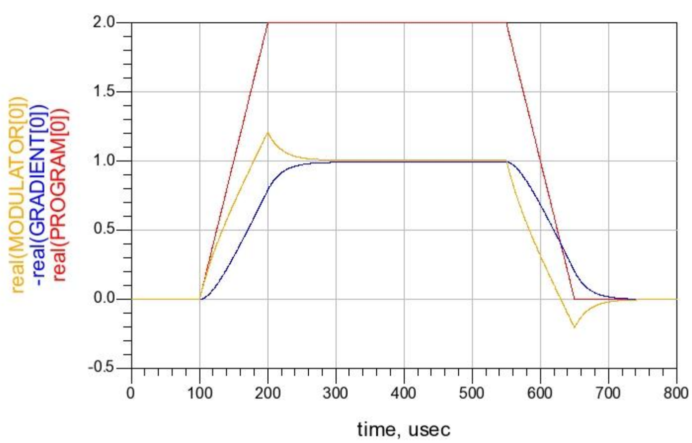

Reverse Power Peaks on Rising & Falling Edges
with β=1.8 (overcoupled) and Forward Power of 3 MW
Reverse Power (MW)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
100
200
300
400
500
Rise or Fall Time (μs)
Rising
Falling
Flattop
Rising Limit
Falling Limit

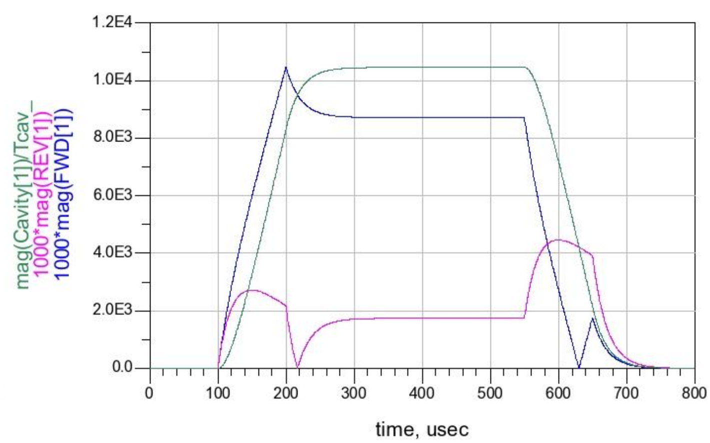

Reverse Power Peaks on Rising & Falling Edges
with β=1.8 (overcoupled) and Forward Power of 3 MW
Reverse Power (MW)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1
10
100
Rise or Fall Time (μs)
Rising
Falling
Flattop
Rising Limit
Falling Limit

Feedback

The cavity fields needs to be settled to < 1% by the time beam arrives. Without feedback, or some form of active feed forward, the cavity fields can take up to 150 us to get within one percent, where as feedback can reduce that number to less than 65 us, which is about 2 cavity time constants.

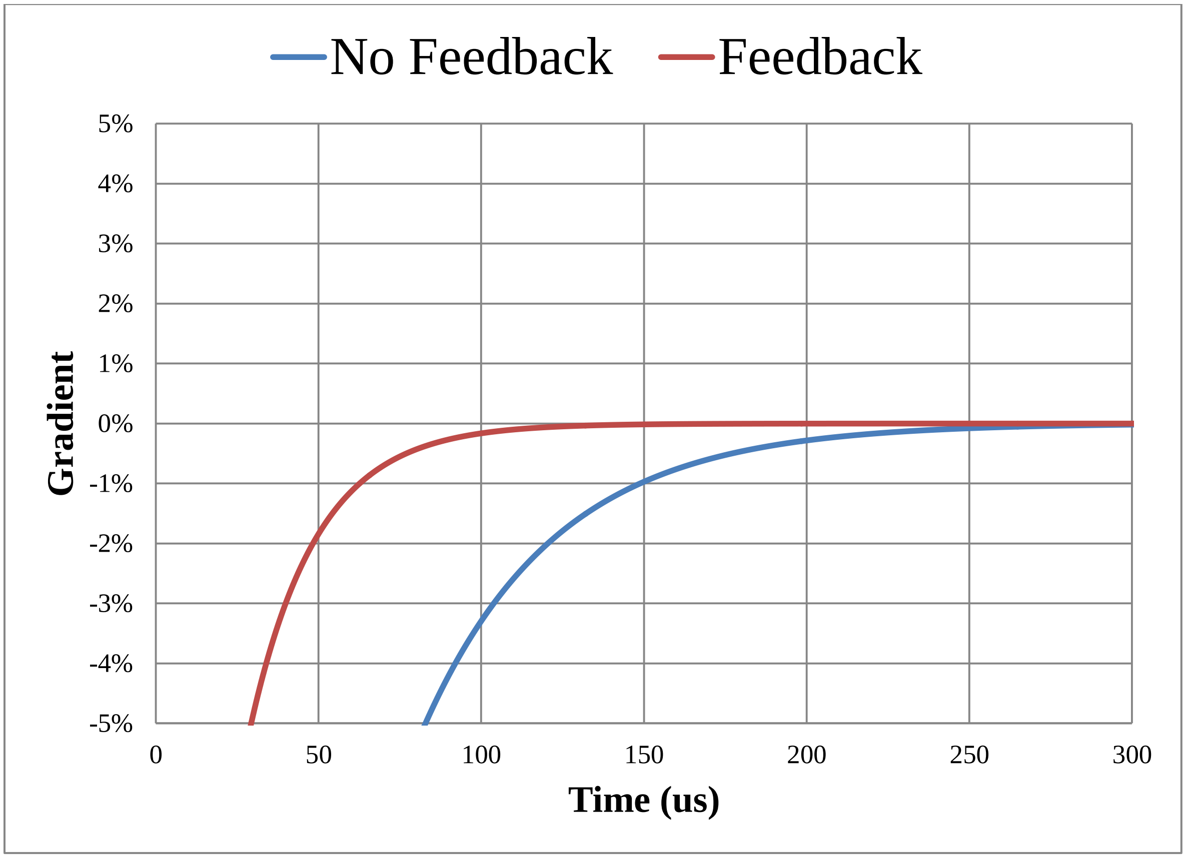






We know from earlier calculations that the cavity time constant is; $\tau_{cavity} = \frac{2Q_L}{\omega_0} = \frac{2 \cdot 23602}{2\pi \cdot 201.25 \times 10^6} = 37.33\ \mu s$

We know from theory about 4.5 times τ equals 1% error, which is around 150 µs, which closely matches the simulation results below. This graph shows that feedback is necessary to stabilize fields before the natural response of the system. Also, we at a miniumum, need about 40 µs between peak time and beam time.



Flat Top Time (50-160 us)

This parameter is ultimately limited by the flattop time of the HE Klystron RF Linac systems (~125 us on modulator voltage (about 80 us of RF with present settings) The flat top time needs to be long enough to account for the maximum beam length and the settling time of the RF cavity fields. Assuming a maximum beam length of 110 us, a settling time of 40 us, and at least 10 us of stable field after beam exits for LLRF calculations, a final specification of 50-160 us was decided.

Beam Length/Time (110 us max)

This parameter was increased to 110 us for the final specification to provide overhead for future linac injectors.

Beam Time Delay (100 us max)

Assuming the modulator runs with a flat top time of 160 us, and beam was up to 60 us in length, that would give a maximum delay of about 100 us. This parameter is important since there needs to be a delay before beam enters the cavity to give the fields time to stabilize and for the LLRF system to do pre-beam measurements.

Peak Voltage Time (35-150 us)

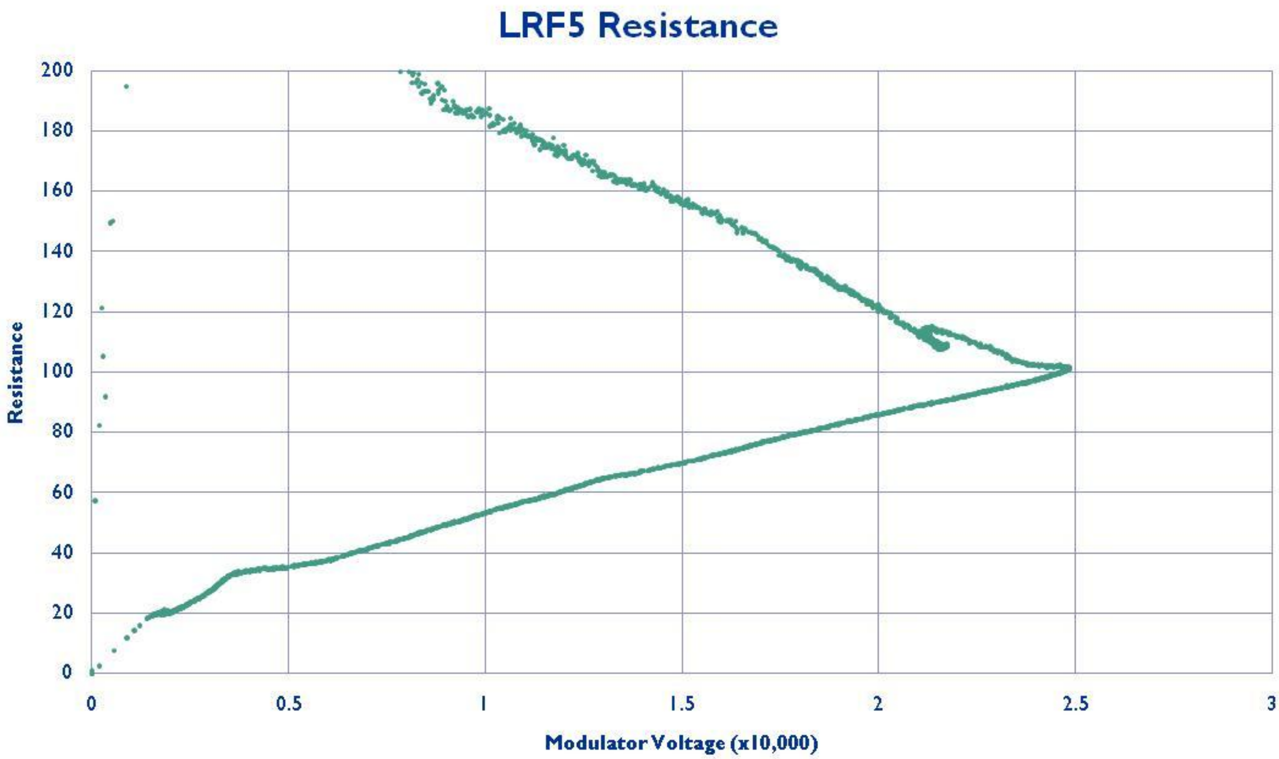
Depending on the age of the 7835, this parameter currently varies to keep gradient stable by increasing the power to the tube during turn-on. This parameter will not exist on any direct RF feedback topology as is currently done.

Output Voltage (8-35 kV)

Currently we run anywhere from 11 to 24 kV flattop voltage [plus up to 10 kV extra for beam (11-34 kV)] for LRF1-5 at nominal operating gradients. Some stations have voltage peaks up to 32 kV, and this number can approach 34 when a 7835 tube gets old and needs maximum voltage to get the required RF energy out. The present system runs as a series pass regulator, where the modulators can't produce more than 34 kV, the switch tubes can only hold off about 42 kV. This is because most switch tubes can only drop a minimum of about 8 kV across them at full power. Another reason for the upper limit is that the 7835 cavity sockets break down at >35kV.

Output Current (375 Amp max)

The output current is entirely dependent on the impedance of the 7835 Power Amplifier (PA). The tube can range from 80-120 Ohms during typical forward powers between 2-3 MW. This impendence can drop below 80 ohms during the voltage ramp up, and to higher than 120 ohms during the voltage ramp down because the energy in the cavity is fed back into the tube, reducing it apparent impedance.



Beam Voltage Step Size (0-10 kV)

Measured between ~3-8kV of beam voltage step on LRF1-5. This number is dependent on the beam energy gain per station which varies. It also depends on the age of the 7835 PA, which can increase this amount of voltage needed to get enough RF out of the tube to accelerate the beam to the proper energy. Most tubes run around 5kV during normal operation with a 7835 in optimal condition

Flat Top Voltage Regulation (+/- 25 Volts)

We measured around 75 Volts on LRF1-5 for a 150 us pulse flat top length. This would be reduced to ~50 Volts for a 100 us pulse. The final specification was set to +/-25 Volts of regulation.

Flat Top Repeatability (+/- 25 Volts)

We measured 200 Volts maximum on LRF1-5 when gradient feedback loops where disabled and during line voltage fluctuations. Decided on a final specification of +/- 25 Volts

Flat Top Resolution (+/- 5 Volts)

We measured between 15-40 Volts between LRF1-LRF2, depending on the station. This makes sense, since we desire 0.1% accuracy. Assuming 25 kV for LRF2-5, we have 25000*0.1% = 25Volts. For LRF1, which has historically run as low as 10kV to get nominal gradient regulation, this number can be as low as 10 Volts = 10000*0.1%, giving a final specification of +/- 5 Volts.

Beam Top Repeatability (+/- 10 Volts)

In the current tube based modulator, this specification is the same as the Flat Top Repeatability. We were not able to measure directly since the machine is always run with the auto gradient regulation loop turned on when running beam. In the new system, this is specified differently since it determines how accurately the modulator needs to regulate the modulator voltage over a range of H- beam currents. It can be assumed that this regulation must be good enough to keep beam energy stable to less than 0.5%. If we have 5kV for a beam voltage typical step size, and we have a resolution of +/- 10 Volts, we have 20/5000 = 0.4% regulation repeatability, which could be regulated down further with the LLRF feedback loop

Beam Top Tilt (+/- 5kV)

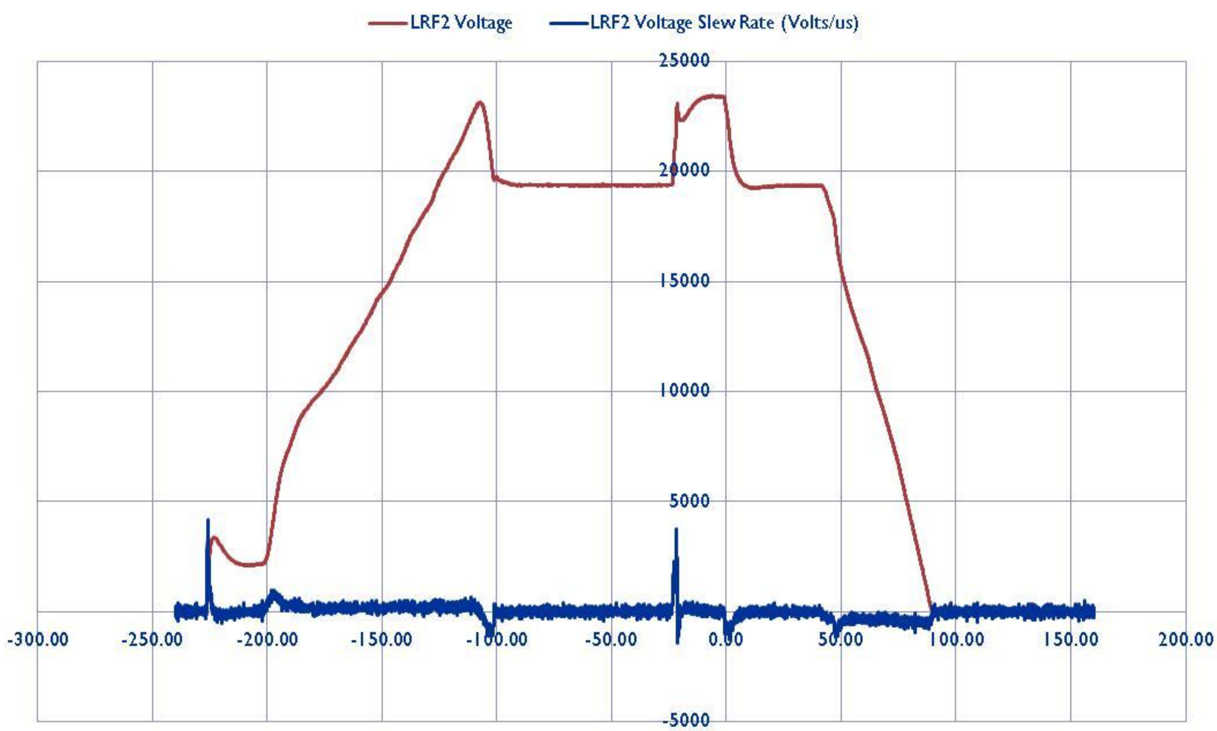
We measured up to 7 kV of tilt on the modulator voltage pulse during beam. This is primarily due to the current feedback loop in the modulator and the roll-off frequency to keep the modulator from oscillating. In an ideal modulator, with ideally square beam, and a 7835 running below anode voltage saturation level, this pulse would be a perfect square. The exception is NTF pulses since they are not square. Although the amount of slope on the RFQ beam is currently unknown, it is expected to have enough tilt to require the modulator to have tilt to compensate. It was decided to leave a beam tilt of +/- 5kV in order to compensate for any, or all, of the non-ideal characteristics of either the RF system or Ion Source

Slew Rate & Step Size

It is desirable to calculate the maximum slew rate on both the rising and falling edges in the cases of a modulator design that use discrete voltage steps on both the rising and falling edges. With a perfect step, the cavity acts as a short/open and returns all of the forward power. Assuming that 30kV maximum is needed to power the 7835 PA to 3MW, then, we can calculate that 10kV steps yield 1 MW jumps of reverse power. Since it is desirable to keep the rising edge reverse power below 0.5 MW, we can only tolerate very small steps since these will add to the waveform. If steps are 1kV per 10 us, we would have spikes of < 100 kW, which would be tolerable. Now, if these steps had a built in physical limitation slew rate of say 500 V/us, we would have a rise time of 60 us for 30kV, which according to the plots above, would keep our reverse power below acceptable limits without a circulator. The falling edge is a different story since it has more reverse power (do to the over coupling of the cavity). Steps of 500 kV per 10 us with a maximum slew rate of 250V/us would be ideal, giving a fall time of 120 us for 30kV. Since this is greater than the current fall time of 100 us, the reverse power would overall be less, allowing for the jumps in reverse power that would come from a step response on the falling edge.

Slew Rate for the Beam Voltage Step (15 kV/us min)

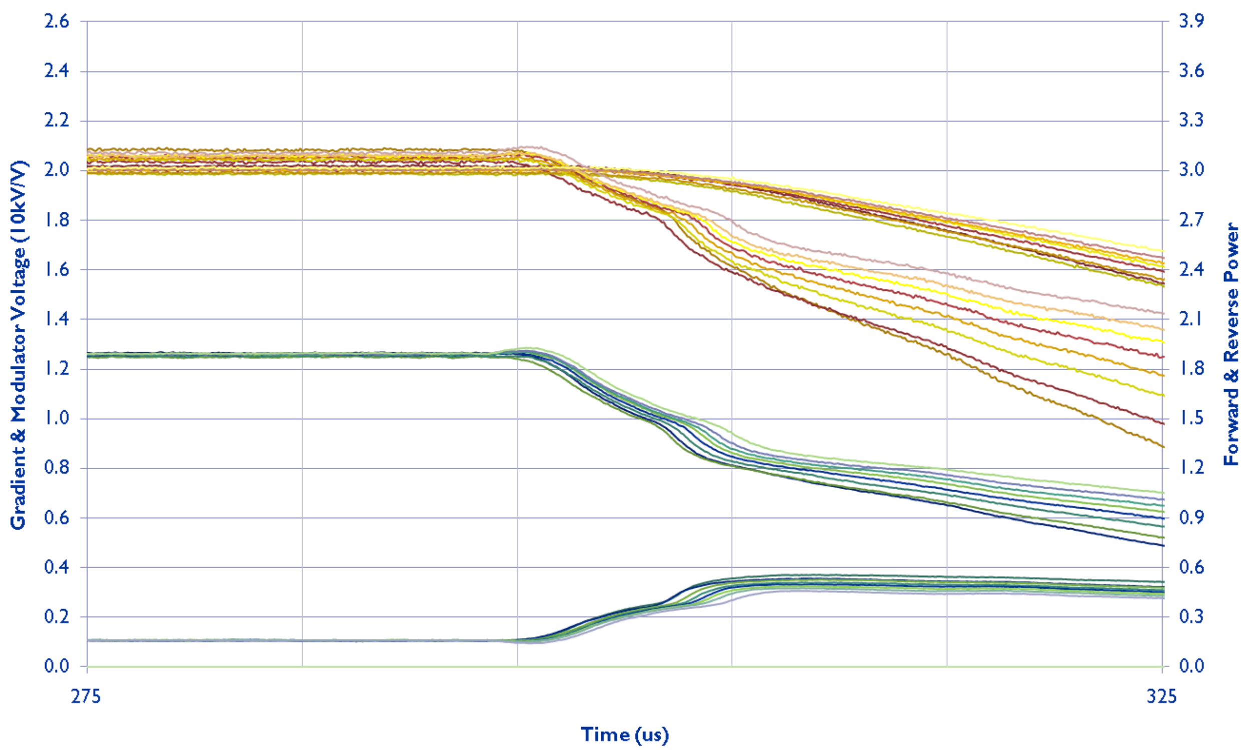
The original specification of the modulator is 20 kV/us. We measured 5-10kV/us on LRF1-5. One of the slowest stations is shown below, with a slew rate of about 4kV/us, which is lower than the actual number due to averaging in the slew rate calculation. This parameter is important since the beam current rises in greater than 1 us, and the modulator needed to be able to jump up to 10kV to compensate for the energy taken from the DTL cavity. A final specification of 15 kV/us was set.



Slew Rate for the Rising Edge (1.0 kV/us max)

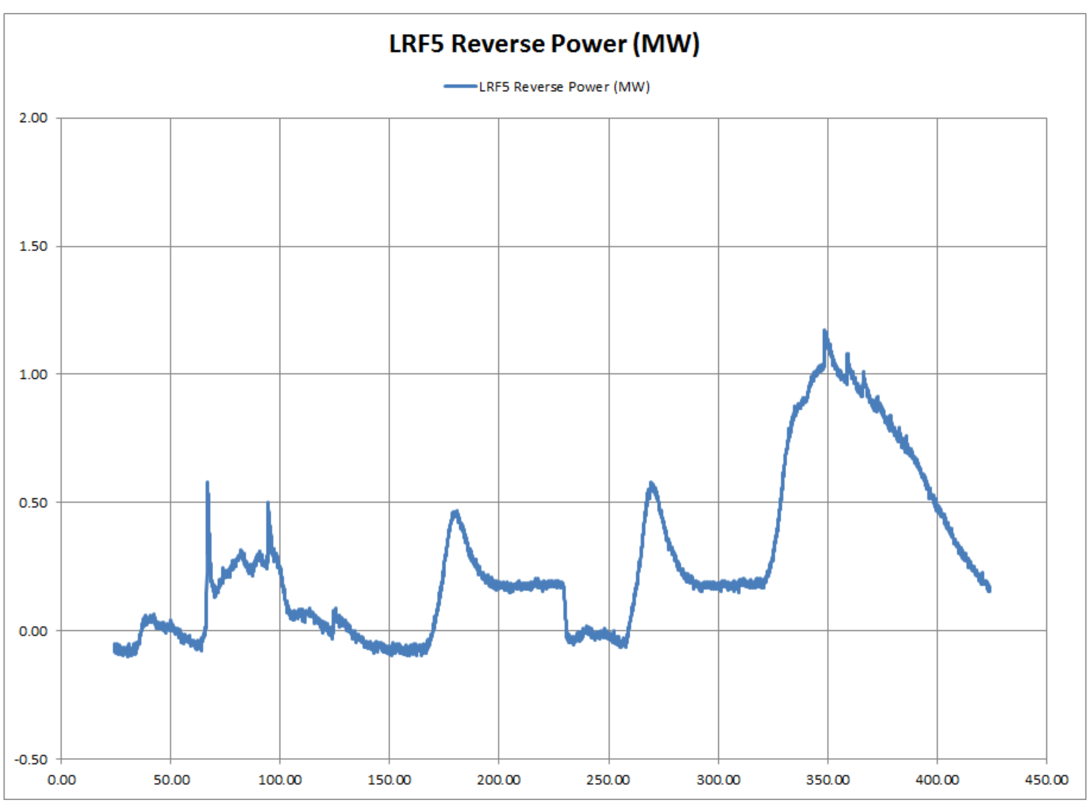
Slew Rate for the Falling Edge (0.5 kV/us max)

It was determined that a slew rate limitation would be needed on the rising and falling and rising edges to reduce the reverse power spikes that occur during those times. From both simulations and tests performed on LRF2 (next slide), we showed that if we increase the fall time, we reduce the peak of reverse power. This reduction is important to reduce the risk of sparking from reverse power spikes that could be created if the modulator is designed with voltage steps. A final specification of 1kV/us on the rise and 0.5kV/us on the fall time was chosen.



Modulator Step Size (1.5kV max)

The parameter does not exist on the present modulator since it does not use discrete stages. If the modulator puts out power in steps, the cavity acts as a short/open and returns all of the forward power. Assuming that 30kV maximum is needed to power the 7835 PA to 3MW, then, we can calculate that 10kV steps yield 1 MW jumps of reverse power. With steps of 1.5kV, we would have reverse power spikes of < 150 kW, which would be acceptable on both the rising and falling edges. A reduction of 150 kW in reverse power is possible when reducing the fall time from 50 us to 150 us, which is the falling edge time specification



Modulator Emergency Off (400 Amps in Pulse & 100 Amps out of Pulse)

Under fault conditions, the modulator needs to drop to zero voltage in less than 2 us. Fault conditions include the RF drive turning off, the 7835 RF cavity sparking, the 7835 internally sparking, the transmission line sparking, or the DTL cavity sparking. There is an out of pulse specification since the 7835 will oscillate in grounded grid mode without RF drive on the tube.

Linearity & Gain

The current specification on linearity was chosen to be +/- 20% to match the previous specification. The current LLRF system has a typical voltage range or 5 Volts, requiring a gain of at least 10000.